

FINAL REPORT¹

[Award No. NAG3-2712]

(Period: November 1, 2001 – July 31, 2004)

MICROSCALE INVESTIGATION OF THERMO-FLUID TRANSPORT IN THE TRANSITION FIL, REGION OF AN EVAPORATING CAPILLARY MENISCUS USING A MICROGRAVITY ENVIRONMENT

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Cleveland, Ohio

July 31, 2004

¹ This Final Report summarizes the progress that has been made by the PI while at Texas A&M University to date and, due to transfer of the PI, additional progress will be continually made at University of Tennessee in Knoxville upon the NASA Award NAG3-2712 is re-granted to the new institute.

Task Abstract/Description

In order to enhance the fundamental understanding of thin film evaporation and thereby improve the critical design concept for two-phase heat transfer devices, microscale heat and mass transport is to be investigated for the transition film region using state-of-the-art optical diagnostic techniques. By utilizing a microgravity environment, the length scales of the transition film region can be extended sufficiently, from submicron to micron, to probe and measure the microscale transport fields which are affected by intermolecular forces.

Extension of the thin film dimensions under microgravity will be achieved by using a conical evaporator made of a thin silicon substrate under which concentric and individually controlled micro-heaters are vapor-deposited to maintain either a constant surface temperature or a controlled temperature variation. Local heat transfer rates, required to maintain the desired wall temperature boundary condition, will be measured and recorded by the concentric thermoresistance heaters controlled by a Wheatstone bridge circuit. The proposed experiment employs a novel technique to maintain a constant liquid volume and liquid pressure in the capillary region of the evaporating meniscus so as to maintain quasi-stationary conditions during measurements on the transition film region. Alternating use of Fizeau interferometry via white and monochromatic light sources will measure the thin film slope and thickness variation, respectively. Molecular Fluorescence Tracking Velocimetry (MFTV), utilizing caged fluorophores of approximately 10-nm in size as seeding particles, will be used to measure the velocity profiles in the thin film region. An optical sectioning technique using confocal microscopy will allow submicron depthwise resolution for the velocity measurements within the film for thicknesses on the order of a few microns. Digital analysis of the fluorescence image-displacement PDFs, as described in the main proposal, can further enhance the depthwise resolution.

Task Objective

The primary objectives of this research are:

1. Unique design and fabrication of micro-heater array that allows heat flux measurements with 10-micron spatial resolution.
2. Thorough review and improvement of the previously published theoretical models for local evaporative flux and inner scale thermo-fluid dynamics of an evaporating contact line.
3. Develop a unique, microscale flow field measurement technique by the combined use of a high-speed and optically-sliced CLSM imaging and the innovative MFTV.
4. Application of the developed diagnostic techniques to measure the heat flux distribution and flow field profiles in microscale resolution inside the thin film region of evaporating liquid bubbles.

Task Significance

Numerous technologies, both terrestrial and space-based, rely upon phase change. These technologies include thermal control systems, application of films and coatings and adhesives, chemical and bioprocessing, and pharmaceutical development. The development of these technologies has relied upon the time tested method of trial and error to develop empirical correlations and phenomenological models of bulk behavior. As systems are reduced toward the micro and nano scales, the role of surface forces on system behavior will continue to become more important and there is little data upon which to build new correlations or models. In order to understand the behavior of systems dominated by surface interactions, we need quantitative data of the transport behavior in the transition film region. Understanding the transition region is critical to predicting and controlling the behavior of evaporating liquid films and menisci in microsystems. This improved fundamental understanding will aid in the refinement of design methodologies of capillary-pumped heat transport devices, thereby benefiting not only NASA missions relying upon these in thermal management and power systems, but the rapidly evolving fields of MEMS and nanotechnology.

Task Progress for FY 2001-July 31, 2004

- (1) Design/Fabrication of Micro-Heater Array: A micro-heater array has been designed to fabricate using a photo-lithography/metal deposition technique to etch and vapor deposit platinum films. The photo-mask design has been completed and the fabrication procedure has been planned where the heater array will be packaged on a thin silicon substrate and then the upper face of the substrate will be planarized to form a smooth contact surface. 256 individually controlled heater elements (10- μ m-wide and 5-mm long) are designed to maintain either a constant surface temperature allowing distributed heat flux or a controlled temperature variation under a constant heat flux. A Wheatstone bridge circuit will control each heater element with the temperature-dependent heater resistance value as a feedback signal.
- (2) Implementation of a Confocal Laser Scanning Microscope (CLSM) System: A Perkin-Elmer/Yokogawa Dual Micro-Lens Nipkow Disk CLSM has been recently implemented with the Texas A&M Permanent University Facility Award (\$130,000) granted to PI's Microscale Fluidics and Heat Transport Laboratory. While the conventional confocal microscopy uses a single point scanning and its scanning rate is limited to an order of one frame per second, the innovative Nipkow Disk Design offers confocal full-field imaging at real time up to 120 ips, which allows optical sectioning for micro-fluidic fast moving flows. The dual Nipkow disk CLSM head unit is attached to the ocular port of the Olympus BX-61 microscope system.
- (3) A new optically-sliced micro-PIV system using CLSM has been developed and evaluated for its true optical slicing capability in comparison with the conventional wide-field (non-confocal) microscopy system. For a laminar flow in a micropore of 100-micron internal diameter, a comparative study of both velocity field measurements shows that the CLSM micro-PIV data agrees remarkably well with the predicted parabolic profiles with unprecedented enhancement in the depth-wise image resolution, whereas the wide-field

micro-PIV data substantially suffers from the obscurations caused by the foreground and background images relative to the focal plane.

- (4) Quantitative tracking of nanoparticles has been achieved by using Total Internal Reflection Fluorescence Microscopy (TIRFM). The implemented system shows that 200-nm fluorescence particles can be three-dimensionally tracked: an elaborate analysis of their image intensity determines their line-of-sight locations and velocities, and a robust algorithm for planar particle tracking specifies their lateral locations and velocity components. The technic proves that nanoparticles can be quantitatively tracked within the range of a few hundred nanometers from the solid interface.

Research Impact on America

- **Innovative Technologies Developed: Innovative Technologies Developed**

1. Design and fabrication of 10-micron resolution microheater arrays using a metal (platinum/gold) deposit technique, and their individual control/monitoring using a Wheatstone bridge micro-potentiometer.
2. Innovation of optical slicing (less than 1-micron thickness) of three-dimensional Molecular Tagging Fluorescence Velocimetry (MTFV) imaging by the high-speed Confocal Laser Scanning Microscope (CLSM) system using a Nipkow disk.

- **Graduate Student Employment:**

3-Ph.D. students and 1-M.S. student (TAMU)

- **Number of Times Research Presented on Magazine Cover:**

Fluorescence Velocimetry (MTFV):

Journal of Flow Visualization and Image Processing, Vol. 8 (2001), Vol. 9 (2002), Vol. 10 (2003) Begell House, New York.

- **Research impact on American/Earth Benefits:**

Advances in medicine and biology hold the promise for improvements in quality of life from a health perspective. Pursuant to this promise is the rapid testing and development of pharmaceuticals. Development of new medicines is increasingly relying upon automated microfluidic technologies such as the lab-on-a-chip. As with microscale heat transfer systems, the role of surface interactions in medical applications is increasing as the length scales decrease. Though the impact of the proposed research on the medical community is far in the future, a more thorough understanding of the transport phenomena in the transition film region will improve the ability to develop new medicines.

Bibliography Information

The whole or partial contents of the following list of journal articles, proceeding entries, theses and dissertations, and presentations have been financially sponsored by the present research award and the NASA Fluid Physics Program sponsorship has been accordingly acknowledged.

• Articles in Peer-reviewed Journals:

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3. Park, J.S., Choi, C.K., Kihm, K.D., and Allen, J.S., 'Optically-Sectioned PIV Measurements Using CLSM,' *Journal of Heat Transfer*, Vol. 125, No. 4, pp. 541-542, 2003.
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• Proceeding Entries:

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6. K. D. Kihm and A. Banerjee, "Tracking of Nanoparticles Using Evanescent Wave Microscopy," HT-FED2004-56652, 2004 ASME-HTFE Summer Conference, Charlotte, North Carolina, July 2004.
7. K. D. Kihm, J.-S. Park and C.-K. Choi, "Nano-PTV Using Confocal Microscopy," HT-FED2004-56653, 2004 ASME-HTFE Summer Conference, Charlotte, North Carolina, July 2004.

• Dissertation and Theses:

1. Lee, H. J., 'Temperature Field Mapping for Microscale Heated Meniscus Using Two-Color Laser Induced Fluorescence (LIF),' Texas A&M University, Department of Mechanical Engineering, August 2003.
2. Wee, S. K., "Microscale Observables for Heat and Mass Transport In Submicron-Scale Evaporating Thin Film," Texas A&M University, Department of Mechanical Engineering, May 2004.

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1. Kihm, K.D., 'Optically Sliced Micro-PIV Measurements Using Confocal Laser Scanning Microscopy (CLSM),' Invited Panelist for Challenges in Micro/Nano-Scale Visualization and Studies, 2003 National Heat Transfer Conferences, Las Vegas, Nevada, July 21, 2003.
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9. K. D. Kihm, "Three-dimensional tracking of nanoparticles for micro/nano/bio-fluidic applications," International Symposium on Particle Image Velocimetry Web Laboratory 2004, Kanazawa, Japan, January 14, 2004.
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